Assessing overheating risk and thermal comfort in state-of-the-art prototype houses that combat exacerbated climate change in UK

Abstract

There is growing evidence that terraced houses—thermally lightweight, well insulated, naturally ventilated with three exposed wall surfaces—are at risk of overheating, especially in south-eastern England. The aim of this study is to evaluate the building performance and develop a reliable building simulation, which will be employed in the second phase of the study: developing affordable and feasible passive design strategies to support the energy-efficient building systems of the construction industry. This paper reports on the results from the first phase of the study where a quantitative methodology, including indoor and outdoor environmental monitoring, in-situ measurements and building simulation modelling, was adopted. The performance of a case study was modelled and simulated via employing Integrated Environmental Solutions (IES) software suite.

The results from the base-case were analysed according to the adaptive thermal comfort of Chartered Institution of Building Services Engineers (CIBSE) Technical Memorandum 52 guidelines: The Limits of Thermal Comfort—Avoiding Overheating in European Buildings. The spaces studied within the case study house were observed to exceed the acceptable limits of thermal comfort; particularly, the large bedroom within this zone exceeded the upper limit for overheating up to 11 hours daily. Furthermore, the results from the monitoring study indicate a high risk of summertime overheating across all the case study settings, especially during short-term peaks in outdoor temperatures. The main reasons for the problematic thermal performance were identified as well-insulated and fully air-tight building fabric, the lack of sufficient ventilation through the living spaces and excessive heat gains through the composite cladding material.

Keywords: Building performance; Overheating; Heat wave; Social housing; Thermal comfort, Retrofit.

1. Introduction and research context

The UK has been facing a housing crisis for some time due to changes in its social housing construction practice policies in recent years. After the construction boom in social housing in the 1950s through the 1980s to meet the demand of its growing urban population, government policies have changed; both construction of new housing and the existing social housing development schemes have stopped, and the existing social housing estates have been privatised over to construction companies. This has resulted in a significant decrease in available social housing, paralleling high private rental accommodations and unaffordable housing prices. Moreover, a government statistical report states that there is a need for 2 million housing units to accommodate housing demands; however, they must also offer affordable housing schemes with liveable indoor conditions that consider people's wellbeing and health, as well as the threat from climate change [1].

In order to tackle the growing housing demand, private construction companies have retrofitted buildings to make more climate resilient and energy efficient residential buildings across the UK while keeping the tenants inside of their dwellings during the retrofitting process [2]. One of the main reasons is to reduce energy consumption, particularly heating demand in the winter, without having to account for the effective passive ventilation system of the building [3]. However, some retrofitting initiatives changed both the social and physical structure of the built environment. For example, the tenants have been forced to move to different diverted locations that are compact and thermally insufficient living spaces because of the redevelopment of the area for different purposes. These changes in the social housing sector have led to a housing crisis and substantial reduction in the number of newly available and affordable housing units, which has also had a significant impact on the designing of more sustainable and resilient communities to meet the demand of this social housing retrofitting gap. Large-scale residential building projects have been put into practice, particularly in the greater City of London. So far, at least 127,000 residential buildings in London have been improved, which in turn, has contributed to saving 46,000 tonnes of CO_2 emissions annually [4].

The main reason for retrofitting these new types of residential buildings is to combat energy consumption in winter, reduce CO_2 emissions and overall reduce household energy bills, which are rising globally due to reduced fossil fuel reserves worldwide [5]. The existing social housing plans from previous decades were thermally insufficient, where the building material for insulation was not compatible with UK climate change scenarios [6]. This has affected the most vulnerable of the population, i.e. the elderly and unemployed people with disabilities, all of whom fall into the low-income energy poverty group [7,8]. Global climate change has affected the UK in recent years in the form of extreme weather conditions. The Met Office's 2018 statistical data shows that February 2018 was the coldest month in 70 years, with temperature plummeting to -14°C [9]. This created a high demand for heating energy, and the energy reserve supply was unable to meet the demand, meaning many households and transportation systems suffered power cuts across the UK. Further, the UK faced exacerbated heatwaves of 35°C and above in June and July 2018, together with the longest recorded drought between the 13 April 2018 and 21 July 2018 [10]. Across the UK, the social housing stock has been refurbished and retrofitted with improper cladding and newly built houses fitted with large glazed window surfaces, including highly thermally insulated external walls. During the 2018 heatwave, both building types had a very high indoor temperature, resulting in relatively high indoor thermal discomfort levels that affected the wellbeing and health of occupants. The overheating of these buildings shows that there is a need for effective passive ventilation or mechanical cooling systems to be fitted in all types of buildings to make them comfortable in all types of weather conditions.

Homes from the southeast of England to the north of Scotland are at risk of overheating during the summertime [11,12]. Excess heat affects the health and wellbeing of occupants, especially if nightly sleep is disrupted. In extremis, heat stress can lead to premature mortality, especially amongst more vulnerable members of society [13]. As the climate warms and heatwaves become more frequent and severe, the problem will become more pressing, heat-related deaths could triple by 2050 if action is not taken [14]. The Committee on Climate Change's (CCC) Adaptation Sub-Committee has recommended to the UK government that 'more action is needed' to reduce overheating risks of buildings in order to minimise the impact on occupants' health and wellbeing [15,16].

Newly-built dwellings are particularly vulnerable, and flats and apartment buildings can suffer from chronic temperature fluctuation in summer [17]. A number of factors combine to create the problem. The potential to ventilate adequately is restricted due to limited operable window areas, external noise and pollution and geometries that preclude cross ventilation into the buildings [18-20]. Additionally, expanding urban areas creates a heat island effect in the cities, which generates elevated temperatures, curtailing night time ventilation for cooling of the occupied spaces [21]. On the other hand, the need to prevent winter heat loss through the already-insufficient building envelope, reduce heating energy demands and so reduce greenhouse gas emissions results in increasing levels of insulation [22]. There is also greater use of thermally lightweight construction techniques, which speed the construction phase and may improve buildings' thermal integrity, as well as a desire to simplify designs and reduce costs, which mitigates, for example, external shading. So-called modern methods of construction for the implementation of state-of-the-art technologies on the building envelope, in which elements of the building, or whole rooms, are constructed off-site, exemplify this approach. It is worth noting that living spaces are becoming smaller, with lower ceilings, which results in higher internal heat gain from occupants, appliances and the hot water distribution pipework [12]. The risk of overheating in UK terraced houses and flats is a well-known industry problem [23,24] and has been a concern of the UK government for some time [25]; however, the problem remains largely unreported on in the literature [19].

The risk of overheating and its impacts on occupants' thermal comfort is already a problem in a residential building prototype tested across different climates in Europe [26]. Many studies have been carried out with the aim to understand those thermal comfort levels that trigger occupants' actions and to classify them [27-29]. These studies demonstrate that one of the major unresolved issues regarding overheating concerns the insufficient building envelope and building systems (e.g. windows, shutters). There are also records to suggest that European residential building stock that have undergone 'systemic retrofit' schemes to improve the thermal performance in winter are now facing overheating issues in summer. The pilot study represents the energy consumption for the heating and cooling of a mid-floor flat in different countries in Europe when accounting for the climate change predictions of 2020, 2050 and 2080 [26]. The findings highlight that the use of domestic appliances in residential buildings created high internal gains that led to an increase in the predominance of cooling loads even in mild climates across Europe. This can further exacerbate climate change aggravated temperature rises scenarios and urban heat island phenomena. However, it has been suggested that the implementation of passive design strategies, such as natural ventilation, are viable options to mitigate those overheating issues related to climate change in residential buildings [30-32]. Researchers who analysed the overheating issue in mild climates emphasize the possibility of adopting 'passive design strategies' that can be effective in avoiding or reducing the need for mechanical systems for cooling in the summer. Another pilot study assessed energy use and overheating risk in net zero energy residential buildings under the Horizon 2020 research project with case studies in Cyprus, France, Italy and the UK on design, optimization, implementation and monitoring of advanced energy efficiency solutions to upgrade the building envelope of inefficient residential building stock [20]. Studies carried out in representative dwellings found that overheating or summer 'discomfort' are major issues both in existing dwellings and newly-built dwellings. The findings also report that there are major heat losses through single-glazed window openings and un-insulated walls in existing dwellings [33].

From the above-mentioned information, it can be surmised that the EU's overall CO_2 emission is relatively higher than other developing countries. As EU policy states, 40% of energy consumption is from residential buildings in overall Europe, but it has set a reduction goal for 2020 [34]. This also applies to existing residential building stock in the UK. At the same time, the UK has put forward its own reduction target of CO_2 emission by 80% by 2050 [35]. In order to reach this target, the aim in the UK is to reduce then completely eliminate the use of fossil fuels by replacing them with renewable energy resources such as solar, wind and biomass [36,37]. The foremost aim is to design and construct buildings with ample thermal comfort in all types of climates without the need for high energy use. There are many different types of these versatile designs which can be applied to the different climate and geographical needs of the UK.

This study evaluates the building performance of one prototype social housing project, based at the Building Research Establishment (BRE) Innovation Park, Watford, United Kingdom. This project is in collaboration with Tigh Grian Ltd in Scotland and Üserhuus in Switzerland. The role of the BRE in this project is to research and display in its park different types of advanced housing prototypes that are energy efficient, affordable and innovative in terms of materials and design with off-site construction technology. At the same time, the BRE showcases state-of-the-art technologies such as Building Integrated Photovoltaic (BIPV) systems, design specifications and regulation guidelines for buildings. One of the main reasons for choosing this type of building project is to construct affordable housing for both the public and private sector, designed to be fully airtight, cost-effective and state-of-the-art with high insulation materials. This prototype house is a representative of a housing project undertaken in both Scotland and Switzerland. Hence, the aim of this study is to research how the above-mentioned prototype housing project can be applied to new terrace type buildings in the UK. The ultimate goal is to replace the current building construction practices in the residential sector, which still employs bricks and traditional timber frame construction that are not energy efficient, less affordable and offer less thermal comfort in climate change. If the traditionally built terrace housing is replaced with this new innovative prototype, it will cut down on household energy bills, be more compact for less land use in densely urbanised areas, affordable and decrease the CO_2 emission of buildings.

Another aim of this research is to investigate the thermal performance of the prototype building to assess overheating in the summer, particularly the long-term heatwave period in the UK. All of this is done to understand the impact of energy efficient technologies on occupants' wellbeing and health in order to identify occupants' thermal comfort level in these types of dwellings. The study seeks to identify the potential improvement of thermal comfort and reduced high indoor air temperatures associated with natural ventilation through a combination of building fabric enhancements (i.e. shading systems and locally available cladding material types for the external walls). In this study, the applicability of the building envelope material choice has been extended to take into account and demonstrate how the orientation of the case study building becomes a vital component when assessing overheating, supported by the critical insight of occupants' energy use variations. This may require an assessment methodology to measure overheating in an occupied space [38]. The measurement of 'overheating' for indoor thermal comfort be independent of the metric used to assess the energy performance of residential buildings; however, the more we can learn about the manner of both cost-effective and energy-efficient building systems' impact on occupants' thermal comfort, the closer we will be to prioritizing the most effective solution to overheating problems [39].

2. Research methodology

The research project is undertaken in three phases: the first phase identifies the existing energy performance of the prototype house and develop a reliable building simulation model for both the second and third phases. At the same time, this first phase sets out to assess the overheating risks and issues with indoor thermal comfort. The study adopts a quantitative research design based on indoor monitoring, in-situ measurements and dynamic simulation modelling. The monitoring of indoor air temperature and relative humidity (RH) levels of the case study provides an in-depth investigation of the indoor environment conditions and validates the results from a simulation analysis of the occupied spaces, in that the monitored rooms reported relatively high indoor temperatures, which are not appropriate for occupants' thermal comfort. The in-situ measurements were carried out to measure ambient air temperature during a long-term heatwave. This detailed information is then used in the dynamic simulation modelling using the Integrated Environmental Solutions (IES) software suite to provide an in-depth understanding of the impact of material properties used in energy efficient building systems and technologies on building energy performance, as well as how this should be considered for appropriate retrofit delivery to combat exacerbated climate change.

2.1. Research case study

The research case study is located in southeast England and sits at latitude of 51°42'N and longitude 0°22'W, as shown in Fig. 1. The prototype building is a two-storey, semi-detached terrace house located in the BRE Innovation Park, which is surrounded by other innovative housing projects. The prototype building is positioned between the car park and the Innovation Park's landscape area, as shown in Fig. 2.

Fig. 1. The case study building.

Fig.2. The location map of the BRE Innovation Park.

This prototype house was assembled on-site in 24 hours in 2015. At the same time, two different halves of prototype houses were assembled with similar construction characteristics. Type A prototype house is a two-storey, semi-detached, with three bedrooms for four persons. Type B is a three-storey with four bedrooms for six persons, as shown in Fig. 3a and 3b. Type A is designed with the ground floor consisting of a living room, an enclosed kitchen and dining area, including a Water Closet (WC). There is also a separate space allocated specially as a battery room for energy and storage systems. The first floor consists of three bedrooms (large, medium and small bedroom spaces) and one bathroom with a WC. There is also a separate space to accommodate the Mechanical Ventilation Heat Recovery (MVHR) system. The internal gross floor area is 86.9m^2. The roof is made out of terracotta Building Integrated Photovoltaic (BIPV) solar panel systems. It is designed to include an empty space between the roof and the ceiling on the first floor. The ground is constructed of composite cladding, while the first floor's external surface is constructed out of timber cladding. The heating system of the whole building uses electricity obtained from its roof solar panels. To facilitate indoor air circulation, there is a MVHR system placed on the first floor.

(a) (b)

Fig. 3. (a) The tested and simulated ground-floor areas; the locations of the installed recording equipment for indoor and outdoor environmental conditions are indicated. (b) The tested and simulated first-floor areas.

The Type B prototype house's ground floor has a combined living room and dining area, enclosed compact kitchen and a WC. On its first floor are two large bedrooms and a bathroom. Additionally, there is a separate space for the MVHR system to facilitate ventilation for the whole building. On the second floor there are two medium bedrooms with a WC. The internal gross floor area is 106.7m^2. The heating of the building is facilitated by a gas system. It consists of mastic roof tiles. The external surface area of the whole building is constructed out of composite panel systems. Both Type A and Type B have similar construction materials; the original U-values are 0.15W/m^{2}K for external walls, 0.14W/m^{2}K for floors, 0.09W/m^{2}K for the roof, 1.00W/m^{2}K for windows and 1.80W/m^{2}K for external doors within an infiltration rate of 1.00-1.50 m^3/m^2/h$^{-1.}$ For this research, the Type A prototype house was chosen in order to test the efficiency of the BIPV solar panel systems because the measurement devices had been installed in Type A only. These devices were installed in 2017, but no measurement figures were extracted or examined until this research project was undertaken in June and July 2018.

2.2. Field studies

This field study was undertaken in two separate sections running parallel to each other for the duration of 25 June-20 July 2018. In order to facilitate this field study, many different types of monitoring devices were installed. The placement location of these devices is shown in Fig. 3a and 3b in Section 2.1. It must be noted that in 2017, Tensor Ltd, which is a company specialising in monitoring energy use in buildings in the UK, installed its monitoring devices to measure the energy consumption, including electricity, gas and heating of this prototype house. The Tensor Ltd monitoring devices consist of a software system called Heating Save Dashboard, which is attached by a wireless system to a heating save extractor. Devices were placed both on the ground and first floors of this prototype house.

Tensor provided a daily report of the energy consumption of the building to the BRE, but as these reports were not analysed, no statistical data was available to show energy performance of this prototype house. Hence, when this research was undertaken between June and July 2018, additional monitoring devices were installed both in ground and first floors. These devices are called 'Tinytag' data loggers. The reason for their choice was that these devices specialise in measuring the temperature, relative humidity (RH) and dew point of indoor spaces. Notably, these devices are also sensitive enough to measure overheating risks, particularly during a long-term heatwave period. These devices were set up to give readings at 10-minute intervals to measure the indoor air temperature during the monitoring period with absolute accuracy.

In Tinytag measurement devices, when compared to the Tensor monitoring devices, no data loss occurs if there is a power cut throughout the monitoring period. In addition to indoor monitoring, the outdoor monitoring was also carried out by using a heating save wireless external temperature sensor to monitor external weather conditions. In-situ measurements were carried out by using Forward Looking Infrared Radiometer (FLIR) infrared thermographic camera to capture the ambient air temperature of both the external surfaces and indoor spaces of the prototype house. The reason for this method is that it gives a reliable measurement of indoor temperature at any given time of any specific surface. The aim is to measure the thermal behaviour of the material the specific surface is constructed from. This Type A prototype house was intensively monitored during the heatwave of June-July 2018 to assess the reasons for overheating, using the collected data for the second phase of the research.

2.3. Building simulation modelling

In addition to both the indoor monitoring and in-situ measurements, the energy performance of the sample rooms was investigated using dynamic simulation modelling with a well-established suite of Environmental Solution's Virtual Environment (IES) simulation software that includes ModelIT, SunCast, Apache, MacroFlo and VistaPro. The expected energy performance of the prototype house and overheating potential were simulated between May and September 2018. In order to validate the data from the first phase, both Type A and Type B prototype houses were modelled using ModelIT in IES software suite, represented in Fig. 4a and 4b.

The case study houses are characterised by a rectangular plan (4.9 x 11.4m) and both are similar in size and form. Each room was modelled separately; this allowed us to tabulate the gathered information in sections and assess overheating risk of occupied spaces accurately. At the same time, the surrounding buildings, including both hard and soft landscape elements in the BRE Innovation Park, were also modelled in order to understand the impact of the local shading factors on the prototype house. The aim is to achieve more accurate data when running the SunCast simulation in IES.

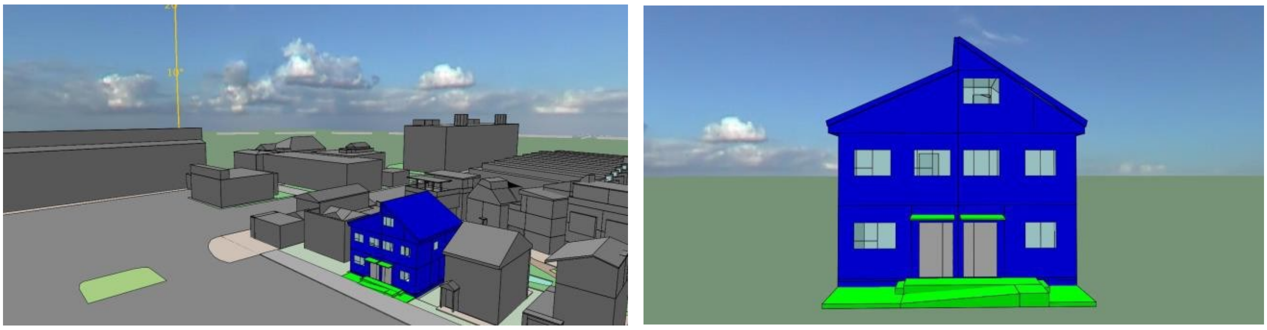

(a) (b)

Fig. 4. (a) The analytical energy model of the prototype Type A and B within adjacent buildings in the BRE Innovation Park. (b) The tested and simulated prototype houses model.

In the modelling of these prototypes, the Apache project construction software interface was used in order to assign the necessary construction materials for assessment of thermal performance in that building. Table 1 demonstrates the details of the thermal properties of construction materials.

Table 1. The list of assigned construction materials into simulation model.

Construction type	**Element details**	**U-value W/m²K**	**R-value m²K/W**	**Thickness mm**	**Mass kg/m²**	**Thermal mass kJ/m²K**
External walls	Earth wool insulation + pine + cellular phenolic (mineral fibre with resin binder) + plaster	0.15	1.46	100	39.1	7.5
Internal walls	Granolithic render/screed + insulated steel stud cavity	1.29	0.53	61.5	52.5	22
Roof	Thermalite (high strength) + pine + roof insulation	0.09	1.25	123	44.5	13.2
Floor	Particleboard (high density) + dense EPS slab insulation + weatherboard + refractory insulating concrete	0.14	2.0	148	67	46.1
Window	Outer pane + cavity + clear float 10mm + cavity + air + cavity + clear float 10mm	1.00	1.18	-	-	-
Ceiling	Vermiculite plastering + dense EPS slab insulation + like Styrofoam + mineral fibre slab + granolithic render/screed	0.38	2.3	148	70.3	34.9

Type A and B prototype houses were modelled in detail by using the ModelIT software interface tool to account for external heat gains from the adjacent Prototype B house. This allows us to calibrate more reliable results to assess both energy performance and overheating risk of the Type A prototype house. The CIBSE Guide A is used as a base-case to model the internal heat gains in the prototype house [40]. Three groups of internal heat gains—lighting, appliances and occupancy profile (professional single)—were modelled (Table 2). The occupancy was chosen to allow for overheating risk assessment of the occupied spaces in the building modelling simulation.

Table 2. Modelled internal gains and occupancy profile.

Space	Internal Gain Category	Sensible Gain	Latent Gain	Occupancy Profile and Number of Occupants
Large Bedroom	People	50.2 W/person	23.6 W/person	10:00 p.m.-7:00 a.m. every day 1 person
	Lighting	18 W		6:00 a.m.-7:00 a.m., 9:00 p.m.-11:00 p.m. every day
	Appliances	20 W		6:00 a.m.-7:00 a.m., 10:00 p.m.-11:00 p.m. every day + 10% best gains for background standby use 24 h/day
Medium/Small Bedrooms	People	50.2 W/person	23.6 W/person	10:00 p.m.-7:00 a.m. every day 1 person
	Lighting	18 W		6:00 a.m.-7:00 a.m., 9:00 p.m.-11:00 p.m. every day
	Appliances	20 W		6:00 a.m.-7:00 a.m., 10:00 p.m.-11:00 p.m. every day + 10% best gains for background standby use 24 h/day
Living room	People	75 W/person	55 W/person	6:00 a.m.-9:00 a.m., 5:00 p.m.-11:00 p.m. every day; 1 person
	Lighting	36 W		8:00 p.m.-11:00 p.m. every day
	Appliances	120 W		6:00 a.m.-9:00 a.m., 5:00 p.m.-11:00 p.m. every day + 10% heat gains for background standby use 24h/day
Kitchen	People	75 W/person	55 W/person	7:00 p.m.-8:00 p.m.
	Cooking appliances	1000 W		7:00 p.m.-9:00 p.m.
	Fridge/Freezer	31 W		24 h/day

For this study, the space heating system was modelled during the cold months (November-March) with a set-point temperature of 23°C, which is the comfort temperature recommended by the CIBSE Guide A [40]. The heating system is turned off during summer months to avoid any interference with the overheating assessment. Mechanical ventilation was simulated for more sensible comparisons in order to demonstrate the predominant occupancy schedules. The dynamic thermal simulations (DTS) account for two types of air transfer: the mechanical air supply and the uncontrolled infiltration. The infiltration was modelled as a fixed flow rate of 0.25 air changes per hour, which is best practice for Üserhuus building standards, indicated by Swiss-Minergie energy efficiency requirements for residential buildings [41]. Based on the concept of a balanced dwelling, the mechanical ventilation extracts and supplies air at an equal flow rate. The extract was from the wet rooms (kitchen, bathroom and WC) and the supply from the dry rooms (bedrooms and living room). This pattern was followed in the living room, large bedroom, medium bedroom and small bedroom. In addition, the MVHR system was modelled with a summer bypass system.

The windows of this prototype house are made of uPVC. They are all prefabricated standard windows. The living room consists of one panel type opening with dimensions of 1.6 x 2.10m. There are two side windows, with restricted openings and dimensions of 0.4 x 0.6m. The kitchen, large, medium and small bedrooms have windows of similar dimensions, but the kitchen window consists of one panel that opens to the outside with a 100% opening ratio; the other panel opening is restricted to just 20% capacity. The large bedroom has a similarly sized window as the kitchen, but the opening of both its panels is 100%. In the other two bedrooms, in accord with the guidelines of the Royal Institution of British Architects' (RIBA) building safety regulations, there is only a 20% opening ratio allowed for safety reasons, as they are specifically classified as children's bedrooms. The ground-floor WC window, for safety reasons, only opens by 20% with dimensions of 0.7 x 0.9m. The first-floor bathroom window has a 100% openable surface area but with similar opening dimensions as the WC on the ground floor to avoid condensation while occupants are taking a shower. Notably, there is a main entrance door made out of timber veneer faced with contrasting stainless-steel ironmongery with dimension of 1.3 x 2.10m. Table 3 demonstrates the detailed information of the assigned opening types with an openable surface ratio.

Table 3. The detailed information of the assigned opening types with an openable surface ratio.

Rooms	Opening	Openable area %	Proportions	Equivalent orifice area (% of gross)
Hall circulation	Window/door—side	100.00	Length/Height < 0.5	35.484
Kitchen window 2, semi-open	Window—top hung	10.00	Length/Height < 0.5	8.387
Kitchen window 1, semi-open	Window—top hung	20.00	Length/Height < 0.5	16.774
Door generic	Window/door—side	100.00	Length/Height < 0.5	35.484
WC & Bathroom	Window—top hung	10.00	Length/Height < 0.5	8.387
Living room side window, single	Window—top hung	20.00	Length/Height < 0.5	16.774
Living room side window, double	Window—top hung	10.00	Length/Height < 0.5	8.387
Living room main openings	Parallel hung windows	100.00	Length/Height = 1	46.237
Large bedroom opening	Parallel hung windows	100.00	Length/Height = 1	23.118
Large bedroom opening, restricted	Parallel hung windows	50.00	Length/Height = 1	9.247
Medium & small bedrooms opening	Parallel hung windows	20.00	Length/Height = 1	4.624
Medium & small bedrooms opening, restricted	Parallel hung windows	10.00	Length/Height = 1	8.387

Following the MacroFlo Calculation methods, the air infiltration rate corresponds to a 0.34 discharge coefficient. It is worth noting that the position of the rooms represents the main variable in the investigation of this study; therefore, the exposure type of the openings was changed depending on the position of the rooms in the prototype house. It is also important to consider the wind pressure co-efficiency rate in relation to the degree of shading from the surrounding buildings in the BRE Innovation Park. Additionally, it is important to simulate the opening pattern of the operable windows in accordance with occupants' operating schedules. In sum, the windows operated in the early morning, late afternoon and evening for the living room and kitchen, and for the bedrooms, the openings were used mainly, during peak occupancy hours in order to represent the dominant occupancy patterns into simulation model. Notably, the windows of the bedrooms and the living rooms were designed to open at an internal temperature of 26°C and 28°C, respectively, only if the external temperature was lower than the internal one. The internal doors were modelled to remain open.

3. Results and discussion

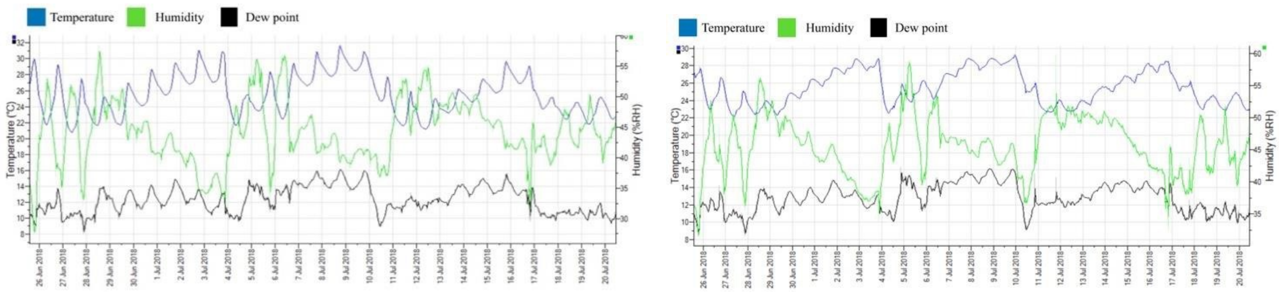
The following sections discuss the results and analysis of data collected from the outdoor and indoor monitoring, in-situ measurements and dynamic simulation modelling.

3.1 Indoor environmental monitoring

3.1.1 Overheating risk assessment

The indoor air temperature and relative humidity (RH) levels of the indoor spaces of this prototype house were monitored between 26 June-20 July 2018 to assess the overheating risks of the building. This monitoring period overlapped with the heatwave period recorded by the Met Office in 2018 as the highest temperature since 1976 [9,10]. In order to understand current overheating risk in the prototype house, data loggers, measuring temperature, relative humidity and, in some areas, CO_2 levels were installed. The Tinytag data loggers were installed in the living room, kitchen, downstairs hall, upstairs hall, large bedroom and medium bedroom to measure the impact of high indoor air temperatures during the heatwave period. Readings were taken every 10 minutes over approximately a month, as previously indicated.

It is important to note that during the monitoring period, the prototype house was not occupied between 9.00am and 17.00pm during weekdays but the windows were given a 20% opening ratio in all the rooms to provide natural ventilation. After 17.00pm, the prototype house was occupied by one person and the window panels of the living room and the main bedroom were 100% open, while the other window panels had a 20% opening ratio due to the security locker allocated on the uPVC window frames. This was to give proper ventilation and avoid overheating of the building. It must also be noted that the Mechanical Ventilation Heat Recovery (MVHR) system was used during the occupancy hours simultaneously with the natural ventilation of the building. Additionally, there was no occupancy during the weekends; hence, all the windows were closed. The analysis of indoor and outdoor temperatures is presented in this section.

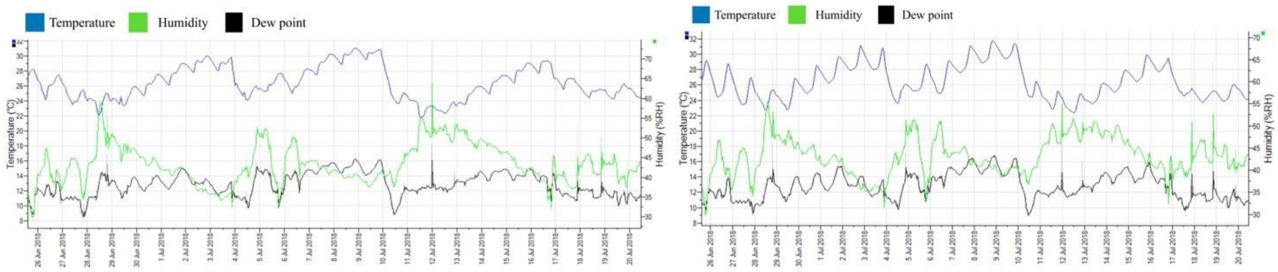


(a) (b)

Fig. 5. (a) The monitoring results of the southwest-facing living room between 27 June-20 July 2018. (b) The monitoring results of the southeast-facing kitchen between 27 June-20 July 2018.

Figure 5a illustrates the monitoring period of the living room, where the thermal comfort level should be between 23-25°C. Therefore, the graph depicts that, starting on the first day of the heatwave on 26 June, the indoor air temperature reached up to 30°C, which does not correlate with the Chartered Institution of Building Services Engineers (CIBSE) Guide A benchmarking, indicating that above 27°C is an acceptable thermal comfort level [40]. There is a serious overheating risk, and these indoor air temperatures negatively the wellbeing of the occupants. This high temperature fluctuated with high and low peaks, but it was always reached above 25°C. This finding demonstrates that the indoor air temperature was over the acceptable comfort level benchmark limit, which is not thermally comfortable for the occupants. Notably, the highest indoor air temperatures were recorded between 7-10 July, reaching up to 32°C on 9 July. The outside peak temperature was recorded by Tensor's Heating Save Dashboard to be 32.68°C at 13.55 hours. Hence, it can be observed that both the indoor and outdoor air temperatures had a similar overheating pattern, even though 27°C is considered an acceptable indoor air temperature for the thermal comfort of residential buildings in the UK [42]. From the graph, it can be observed that at its peak time, indoor air temperature was above this comfort level zone by 5°C. This clearly indicates that due to this prototype house's structural construction material behaviour in a heatwave and its location (southwest facing orientation), it is susceptible to very high overheating risk.

Figure 5b illustrates the indoor air temperature fluctuations of the kitchen during the first day of the heatwave period, 26 June. It shows indoor air temperature peaking at 28°C—just 1°C above indicated benchmark [43]. These fluctuation peaks did not go above 28°C; this is due to its location and position in the building and the impact from other external factors such as its southeast facing and asphalt surface and a concrete wall of an adjacent building where it gets heat reflection. It is important to note that during the monitoring period, the minimum electrical appliances were used; hence, there is no impact from internal heat gains. In particular, all the impact has to come from external environmental factors. From the indoor air temperature fluctuation, it can be observed that temperatures were above 25°C between 30 June-20 July. The highest indoor air temperature was recorded at 31°C on 10 July. The highest outdoor air temperature on that day was recorded at 25.61°C at 19.04 hours. This shows that the outdoor air temperature is slightly lower than the indoor air temperature because of the external environmental factors, the external wall surfaces' insulation material and composite cladding systems which can absorb the reflected heat much more efficiently than other traditional residential building materials.



(a) (b)

Fig. 6. (a) The monitoring results of the southeast-facing large bedroom between 27 June-20 July 2018. (b) The monitoring results of the southwest-facing medium bedroom between 27 June-20 July 2018.

In Fig. 6a, indoor air temperature fluctuations of the large bedroom situated on the first floor on the first day of the heatwave are provided. The indoor air temperature came in at 28°C while the outdoor temperature was 35°C. This indoor air temperature of 28°C remained the same up to 31°C on 9 July where the outdoor air temperature showed at 32.76°C, then peaked down 23°C on 12 July, which is an acceptable thermal comfort level band for the occupants. At the same time, the peak outdoor air temperature was 28.54°C at 15.10pm. This indicates that depending on the position of the monitored room in the building, it can be observed that the high overheating risk decreases. After 2 July, the peak indoor air temperature of this large bedroom increased to 31°C while the outdoor air temperature read 26.50°C at 19.19pm. This is because the MVHR system was not in operation. It can be concluded from these indoor air temperature fluctuations that the indoor air temperature in the master bedroom is not thermally comfortable and can lead to occupants experiencing heat stress at night time. It is important to highlight that this overheating is due to the high heat absorption factor of the insulation material and heat gains from the terracotta BIPV solar panel systems.

Figure 6b showcases the indoor air temperature fluctuations of the medium bedroom during the heatwave period between 26 June-20 July. This shows a similar trend as the large bedroom, even though the medium bedroom's southwest-facing orientation gets more sunshine, is smaller in size and has a single window opening. The peak temperature of 32°C was recorded on 9 July, the hottest day of the heatwave. The outdoor air temperature was 32.5°C at 14.00pm. This again parallels the temperature recordings of the large bedroom. It can be observed from the graph that the overall recorded temperature was above the acceptable benchmark of 25°C to maintain occupants' thermal comfort. Furthermore, the average mean temperature across both the large and medium bedrooms was noted at 24.5°C, above recommended thermal comfort levels [44]. During this monitoring period, it was observed that all the indoor spaces, including the hallway and staircase areas, were at risk of overheating, particularly during the heatwave periods. In addition, it was also observed that the living room and the large bedroom were the most problematic rooms. This is because the living room had large opening window ratios with walls constructed out of composite panel systems, which has a very high absorption rate of solar radiation, while the large bedroom's overheating risk was due to the terracotta roof panels and its timber cladding material on the external surfaces that have Earth-wool infill insulation. The second notable problem was the downstairs hallway and stairwell spaces, which was due to the absence of natural ventilation.

In relation to the static 'comfort' range [45,46] for the non-airconditioned living room and kitchen, the indoor air temperatures in the living room were mainly within the 'comfort' range (25 °C ± 3K), although there were some instances of temperatures above 28°C and below 22°C. Outdoor temperatures were significantly higher throughout the heatwave, with several periods where the temperature was above 28°C and never below 22°C. Inside the prototype house, temperatures were significantly higher throughout the heatwave, with several periods where the temperature was above 30°C and never below 22°C. The average mean temperature across the five monitored rooms was 25.5°C. When cross-examined with outdoor air temperature data, it became apparent that these figures correlated with outdoor temperatures and highlighted the impact of long-term heatwaves on the overheating risk within the buildings [47,48].

Energy efficient technology materials and their systems are best used in winter periods to reduce heating demand. However, indoor monitoring and in-situ measurements indicate that these cost-effective and energy efficient technologies are not applicable for all types of climates. From these indoor monitoring and in-situ measurements, the gathered data can be used for subsequent building simulations of dynamic thermal studies in order to validate overheating risks of the prototype house.

3.2 In-situ measurements

All these calibration studies have been carried out using the SunCast simulation tool platform. In order to validate these findings, in-situ measurements were carried out using a Forward Looking Infrared Radiometer (FLIR) infrared thermographic camera to assess the thermal behaviour characteristics of the materials used in the construction of the external walls and composite cladding material (the insulation used in between the external and internal walls). These in-situ measurements were taken during the high peak heatwave period on 10 July, when high outdoor temperatures of 35°C were recorded. This in-situ measurements also highlighted the temperature readings of the different material types with high U-values. In-situ measurements were taken at

17.30pm, peak temperature time, to capture the effect of high solar radiation on the building envelope. Figure 7a shows composite cladding walls on the ground floor with an outdoor temperature of 43.3°, while Fig. 7b shows timber cladding walls with an outdoor temperature of 38°C. This demonstrates that the overheating risk of the living room and the kitchen is due to the composite cladding on the external wall surfaces.

Fig. 7. (a) The thermal performance of composite cladding on the ground floor. (b) The thermal performance of timber cladding on the first floor. (c) The Lithium-ion energy battery storages are allocated on the ground floor and the battery room temperature was 38.5°C at peak day on 10 July 2018.

Table 4. The results of the in-situ measurements during the peak heatwave period between 5-12 July 2018.

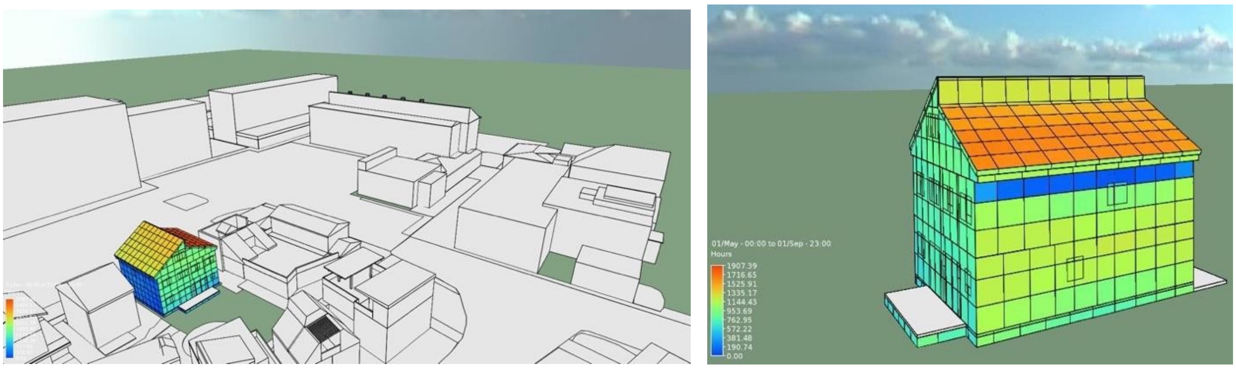
04/07/18	*Temperature* °C		**05/07/18**	*Temperature* °C	**10/07/18**	*Temperature* °C	**11/07/18**	*Temperature* °C	**12/07/18**	*Temperature* °C
Room Name	**Morning**	**Afternoon**	**Morning**	**Afternoon**	**Morning**	**Afternoon**	**Morning**	**Afternoon**	**Morning**	**Afternoon**
Ground Outside	Side: 23.6 Back: 18.5	Side: 22.8 Back: 22.8	Side: 25.5 Back: 24.9	Side: 22.1 Back: 19.3	Side: 23.2 Back:19.6	Side: 18.7 Back: 19.1	Side: 17.0 Back: 17.4	Side: 19.8 Back: 19.9	Side: 23.7 Back: 20.2	Side: 19.2 Back: 20.1
First Outside	Side: 16.8 Back: 17.3	Side: 21.9 Back: 22.6	Side: N/A Back: 25.6	Side:21.4 Back:18.6	Side: 17.7 Back: 20.6	Side: 19.3 Back: 18.6	Side: 16.1 Back: 17.7	Side:19.7 Back: 19.7	Side: 19.6 Back: 21.3	Side: 18.5 Back: 19.8
Room Name	**Morning**	**Afternoon**	**Morning**	**Afternoon**	**Morning**	**Afternoon**	**Morning**	**Afternoon**	**Morning**	**Afternoon**
Living room	27.7	25.5	23.5	26.8	25.6	26.9	29.7	28.9	25.7	29.3
Kitchen	N/A	25	29.1	25.9	26.7	26	28.6	29.4	25.2	28.6
Battery room	31.1	30.9	31	31.1	33.9	31.8	29.6	31	28.5	29.9
Downstairs hall	26.6	25.8	29.8	27.1	25.5	26.6	27.3	26.7	25.2	26.3
Upstairs hall	25.9	26.7	25.7	27.9	25.5	26.4	28.9	27.7	25.7	27.2
Boiler room	28.2	28.7	25.2	30.3	25.1	27.8	25.7	26.8	26.8	26.7
Master bedroom	29.5	26.3	26.8	27.5	26.6	25.3	25.3	28.1	27.6	27.8
Bedroom 1	29	26.4	25.4	28.3	25	27	25.3	25.6	27.8	25.8
Bedroom 2	29.1	26.7	25.6	28.4	25.6	26.9	25.2	25.7	27.7	26.7
****Morning: 09:00-09:30, Afternoon: 20:20-20:40 **clear sunny sky ***cloudy***										

Along with the above outdoor measurements on that peak day during the heatwave taken by the infrared camera, all the indoor spaces' ambient temperature was measured. The results of the in-situ measurements are shown in Table 4. These measurements were undertaken early in the morning and late in the evening so as to avoid direct sunlight, which does not give an accurate measurement because the aim of this study is to achieve accurate ambient air temperature readings of the indoor spaces in this prototype house. It can be observed from Table 4 that all indoor spaces show high indoor air temperatures. The highest temperature has been recorded in the battery room on the ground floor. It is because of the presence of the energy storage battery, for storing electricity from the roof's terracotta BIPV solar panel systems, that the room temperature was 38.5°C at peak day, as shown in Fig. 7c. The location of this battery room on the ground floor is therefore an added factor in the overheating risk of the living room and kitchen. Another interesting finding arose when the measurements were taken early in the morning with a clear, sunny sky; the temperature of the external walls was 23°C, the maximum acceptable level for thermal comfort [42,43]. As shown in Table 4, all indoor temperatures were above 25°C. This proves that even in early morning sun, there is a high risk of overheating.

3.3 Building simulation analysis

3.3.1 Solar analysis and overheating risk assessment

In the building simulation modelling, the SunCast software interface tool was used to assess the amount of solar radiation absorbed by any given external surface of the prototype depending on its orientation and the effect from adjacent buildings. The SunCast analysis was carried out on this building for the whole year of 2017 in order to gather a more accurate number of sunshine hours absorbed by the prototype house. The roof absorbed the most excess solar heat gains in the summer, as shown in Fig. 8a and 8b.



(a) (b)

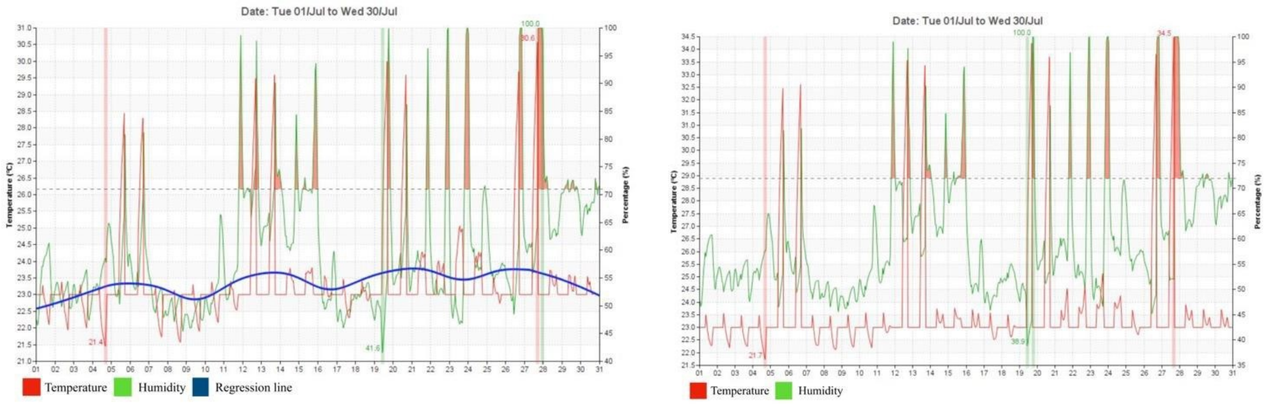
Fig. 8. (a) SunCast simulation demonstrating the prototype house's annual number of hours of solar radiation exposure. (b) SunCast simulation demonstrating that the monthly exposure to solar radiation exposure on the southwestern façade reaches 1,907.38 hours total between May and September 2017.

This absorption was due to the orientation of the building, as the roof faces south and was constructed out of terracotta BIPV solar panel systems. The external walls were insulated using fermacell board on the inside and outside, with Earth-wool infill in between to provide efficient thermal performance in winter. This Earth-wool infill is a highly efficient insulation material; its purpose is to decrease heat loss and keep the indoor spaces warm. As this prototype is a semi-detached house, only three external surfaces are exposed, and all three surfaces have similar heat gains throughout the year with exacerbations in the summer. This comes with overheating risk due to the high insulation factor of the Earth-wool infill material. Additionally, the first-floor spaces showed the highest overheating risk issues due to the impact of the double insulation structure of the roof, as BIPV solar panel systems are placed on top of its original surface. Hence, all the bedroom spaces on the first floor are under a higher threat of overheating when compared to the CIBSE TM52 overheating criteria [49].

It is important to highlight that the living room is also susceptible to the same risk of overheating, but it is affected by different factors, in that it has large window opening ratios with no shading systems and all of them face the southwest project site in the BRE Innovation Park. This means that the living room is exposed to a high intensity of daylight throughout most of the day from these windows, while at the same time its external walls, which are constructed out of composite cladding material, are also exposed to high solar heat gains. These factors combined leads to overheating issues and a high level of occupants' discomfort, particularly in the summer.

3.3.2 Evaluating the building performance of the prototype house

Building energy and thermal modelling and simulation have been undertaken using Integrated Environmental Solutions (IES VE) software to validate the monitored data against the simulation results. The aim is to develop a viable model to be adopted for the second phase of the study concerning building performance optimisation by embedding passive design strategies for a retrofit of the prototype house. IES is an advanced building simulation tool that has been validated for dynamic thermal modelling of large and complex buildings [50]. The software uses a thermal comfort assessment tool defined by both the CIBSE Guide A and CIBSE TM52 on overheating assessment for the simulation analysis [40,44,49]. The focus of the study at this stage is the hottest week of summer, in July, to predict the indoor air temperature levels and assess overheating risk. The prototype house was modelled in IES using the building materials of the Üserhuus (as described in Section 2.1). The actual ventilation and occupancy patterns of the sample rooms were each incorporated into the model. The Met Office's outdoor environmental data for the weather station at London Luton Airport (the nearest weather station to the building location) was used as the climatic weather file in IES in order to create a feasible model with real outdoor climatic data [50]. To calibrate the building performance, as well as the building materials and components adopted in the model, the measured indoor environment data were scrutinised in conjunction with the IES simulation results.



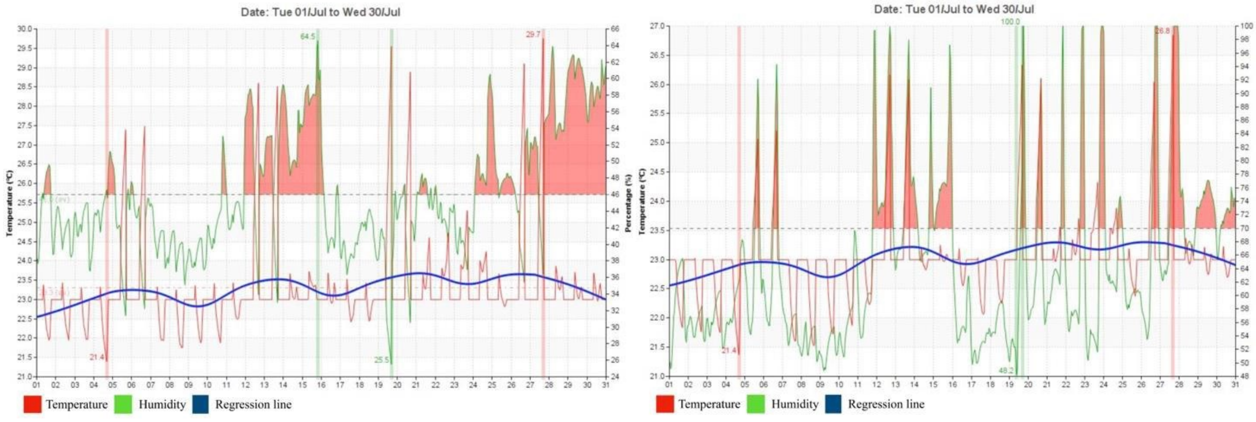
(a) (b)

Fig. 9. (a) Indoor air temperature of living room on the ground floor in July reached a maximum of 30.6°C. (b) Indoor air temperature of kitchen on the ground floor in July reached a maximum of 34.5°C.

In Fig. 9a, the simulation of the indoor air temperature level of the southwest-facing living room can be seen. The line at 23°C indicates the optimum comfort level temperature. Thus, the margin line at 28.1°C is the maximum limit of comfortable temperatures. On the graph shown in Fig. 9a, the space between 23°C and 26.1°C shows the acceptable levels of temperature fluctuations for the occupants' comfort level. The space above the 26.1°C margin indicates overheating risk temperatures. In the first week of July, the temperature fluctuation was stable at the comfort level zone. It shows the lowest peak on 4 July at 21.4°C. This plummeting peak fluctuation continued up until 12 July whereby the peak temperature started to rise above the maximum acceptable benchmark of 26.1°C. This trend continued throughout July, the hottest month. The highest peak indoor air temperature was recorded on 28 July at 30.6°C, which is 2.6°C higher than the 28°C benchmark given by CIBSE TM52 overheating risk assessment guidelines [40,44,49]. Notably, the regression line is positioned just above the lower margin line at 23°C, showing the temperature fluctuation from the internal heat gains. It gives an indication of the impact of these temperature fluctuations on the thermal comfort level of the living room. The lower margin in Fig. 9a is 23°C, and the upper margin is set at 29°C, which is higher than the living room upper margin, due to the internal heat gains from its appliances. The lowest temperature of 21.7°C was recorded on 4 July, but then it peaked above the acceptable comfort band later in the day, and this fluctuation trend continued, with the highest peak temperature of 34.5°C on 28 July. This shows that the living room is highly susceptible to overheating risk because of its southeast orientation, the internal heat gains factors of domestic appliances and the number of lightbulbs.

Figure 9b demonstrates the indoor air temperature fluctuations of the kitchen starting on 1 July at 23°C, then fluctuating between 23-32.5°C until 12 July. On 5 July, peak highs hit up to 32.5°C then plummeted to 23°C in mid-July. The slightly higher indoor temperature recording of 33.5°C was on 13 July, which then fluctuated around 29°C up until mid-July. After this, it decreased to 23°C and continued to fluctuate at this level until the end of July. However, the highest of 34.5°C was recorded on 28 July. Figure 9b's graph, when compared to the other graphs, depicts an intensely changing pattern; this is due to the internal heat gains from domestic appliances. The generated benchmark for the kitchen is 29°C, but in the graph, the overall indoor air temperature of the kitchen was above this generated benchmark at the peak of summer. The monitoring measurements during the peak heatwave found the kitchen to be above 25°C. Hence, the findings indicating the risk of overheating during the peak heatwave is validated.

Figure 10a below illustrates the lower margin at 23.3°C and the upper margin at 25.7°C for the large bedroom. This shows the fluctuations of temperature always being near or above the upper margin line up to 11 July, which then peaks at 28.5°C on 13 July, then dips down and follows this trend up to 20 July, where temperatures peak at 29.5°C. This shows that these temperature fluctuations do not provide night time thermal comfort for occupants' sleep [44,45,46].



(a) (b)

Fig. 10. (a) Indoor air temperature of large bedroom on the first floor in July reached a maximum of 29.7°C.
(b) Indoor air temperature of medium bedroom on the first floor in July reached a maximum of 26.8°C.

Figure 10b's graph shows the lower margin comfort band at 23°C and the upper margin at 23.5°C for the medium bedroom. This allows for a very restricted comfort zone band. It shows the temperature to be in the comfort zone space up to 13 July; afterwards it peaks at 26°C then dips down to 23°C on 20 July. This trend continues to fluctuate in a similar trend where the highest recorded temperature of 26.8°C on 28 July, which is just shy of the benchmark temperature level of 27°C [42,43]. The regression line is initially just below the lower margin of comfort zone of 23°C up to 12 July, then it peaks, fluctuating above the lower margin, with the maximum peak just below 23.5°C. It can be concluded that although there is a potential threat of overheating risk, the overall deductions show it to be within the thermal comfort zone for occupants' night time sleep.

The data collected from simulation studies in Table 5 demonstrates the different thermal comfort levels for every occupied room in the prototype house. The highest temperature was recorded in the southeast-facing kitchen at 36.1°C. This is followed by the living room with 35.8°C; this is due to the external walls being constructed from composite cladding and the presence of domestic appliances in these rooms. Table 5 also shows the Predicted People Discomfort (PPD) levels were much higher than the indicated acceptable comfort levels of CIBSE TM52 thermal comfort benchmarking, which must be 5-10% to provide thermally comfortable conditions for occupants [49]. The highest PPD level in the kitchen is 14.2%, followed by the living room with 10.9%. The hallway of the ground floor shows a temperature of 28.9°C and a PPD of 13.1%.

Table 5. Simulation-based thermal comfort of all occupied rooms in prototype house.

	Temperature		*Relative Humidity*		*Predicted People Discomfort*	
Room Name	**Max °C**	**Min °C**	**Max %**	**Min %**	**Max %**	**Min %**
TYPEA_FIRST_LARGEBEDROOM	32.5	19.8	100	25.2	13.3	5.0
TYPEA_FIRST_MEDIUMBEDROOM	29	19.0	100	25.2	13.1	5.0
TYPEA_GROUND_KITCHEN	36.1	20.9	100	90.4	14.2	5.3
TYPEA_GROUND_LIVINGROOM	35.8	19.3	100	22.1	10.9	5.0
TYPEA_GROUND_CIRCULATION	28.9	19	100	27.9	13.1	11.7

TYPEA_FIRST_CIRCULATION	26.4	19.6	100	34.1	70.4	17.4
TYPEA_FIRST_SMALLBEDROOM	28.3	18.7	100	43.0	13.1	13.2
**** The PPD max limit value is 10%—PPD is the percentage of people who will find the room thermally uncomfortable.***						

On the first floor, the large bedroom showed the highest temperature of 32.5°C with PPD levels of 13.3%. The other two bedrooms have shown similar temperature peaks—the medium bedroom at 29.0°C and small bedroom 28.3°C. This indicates a low level of night time sleeping comfort, as the acceptable optimum thermal comfort level is indicated to be between 5-10%. It is important to highlight that the main concern was the staircases' circulation area, where the temperature was 26.4°C and the PPD level 17.4%. This PPD level was found to be the highest of all the indoor areas from the effect of the terracotta BIPV solar panel systems as well as the absence of natural ventilation, which leads to the storage heat effect and also directly effects the temperature of the nearby spaces.

From the building modelling simulations, it can be observed that the most problematic room was kitchen at 36.1°C, and the next worst was the living room, both situated on the ground floor. At the same time, the same pattern was observed for the large bedroom and the medium bedroom, both on the first floor. When taking into account the CIBSE TM52 overheating guidelines, which gives a representative sample data set based on generic occupancy schedules of thermally comfortable benchmark level at 25°C [49], it can be seen that the heat stress index is slightly higher than the benchmark [42,43].

Table 6 shows the overheating results for each criterion using the adaptive comfort method [51,52]. The results indicate that overheating is major problem for the prototype house during a long-term heatwave based on the current design and construction parameters. The Type A prototype house also showed some risk of overheating in the living room, particularly in the late afternoon. While the front facades of the houses face southeast, the decking area faces southwest. Found in all designs of this innovative housing are large, double uPVC-made glass doors in the living room facing the garden as well as larger windows in other rooms. This could help explain the greater overheating in the living room as compared to the bedrooms. Notably, both the medium and small bedrooms are also southwest facing and overheat a bit more than the large bedroom on the first floor.

Table 6. Simulation-based summertime overheating results for the prototype house.

Room Name	**Criteria 1**	**Criteria 2**	**Criteria 3**	**Criteria failing**
	(%Hrs Top-Tmax > = 1K)	(Max. Daily Deg. Hrs)	(Max. ΔT)	Criteria failing
TYPEA_FIRST_LARGEBEDROOM	1	14	4	2
TYPEA_FIRST_MEDIUMBEDROOM	0	0	0	-
TYPEA_GROUND_KITCHEN	3.4	27	8	1 & 2 & 3
TYPEA_GROUND_WC	4.1	29	8	1 & 2 & 3
TYPEA_GROUND_LIVINGROOM	2.2	19	7	2 & 3
TYPEA_GROUND_ENERGYSTORAGE	34	52	9	1 & 2 & 3
TYPEA_GROUND_CIRCULATION	5.4	22	7	1 & 2 & 3
TYPEA_FIRST_BOILERROOM	87	113	9	1 & 2 & 3
TYPEA_FIRST_BATHROOM	84.2	124	10	1 & 2 & 3
TYPEA_FIRST_SMALLBEDROOM	12.3	32	8	1 & 2 & 3

The building simulation of the Type A prototype house was done at the same time as indoor environmental monitoring and in-situ measurements in order to validate the data from dynamic thermal simulations (DTS) and to assess overheating risk issues during a heatwave. The quantitative triangulation research method shows that there are signs of overheating risk across all the occupied rooms in the prototype house. In order to evaluate the correlation between different simulation parameters, Pearson (2-tailed) correlation analysis was conducted in the Statistical Package for the Social Science (SPSS) software. Only few parameters had strong correlations that could be applied to all the occupied rooms. To fulfil the research objective, only the monitored date/time measured against indoor operative temperature and outdoor operative were filtered out for further investigations in order to validate the greater risk of overheating from the building modelling simulation. Table 7 summarises the correlation results; a better correlation was found between indoor operative temperature when compared to that of outdoor temperature. The relationship was stronger for the battery room than for the other three monitored rooms. In addition, the living room was found to have the best correlation between indoor and outdoor operative temperature ($p < 0.01$).

Table 7. Correlation results for indoor air temperature of occupied spaces at the Type A prototype house.

Indoor operative temperature		**Correlation Coefficient**				
		Monitored_date	**Livingroom**	**Batteryroom**	**Largebedroom**	**Kitchen**
Monitored_date	**Pearson Correlation**	1	0.218**	0.477**	0.193**	0.306**
	Sig. (2-tailed)		0.000	0.000	0.000	0.000
	N	1488	1480	1475	1477	1477
Livingroom	**Pearson Correlation**	0.218**	1	0.741**	0.911**	0.936**
	Sig. (2-tailed)	0.000		0.000	0.000	0.000
	N	1480	1480	1474	1477	1477
Batteryroom	**Pearson Correlation**	0.477**	0.741**	1	0.784**	0.862**
	Sig. (2-tailed)	0.000	0.000		0.000	0.000
	N	1475	1474	1475	1474	1474
Largebedroom	**Pearson Correlation**	0.193**	0.911**	0.784**	1	0.944**
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000
	N	1477	1477	1474	1477	1477
Kitchen	**Pearson Correlation**	0.306**	0.936**	0.862**	0.944**	1
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000
	N	1477	1477	1474	1477	1477

**. Correlation is significant at the 0.01 level (2-tailed).

The correlation was considered to be statistically significant for $p < 0.01$. There appears to be a strong and positive correlation between the risk of overheating and thermal comfort across the monitored rooms ($r = 0.944$, $p < 0.01$), while there is a moderate correlation in the large bedroom ($r = 0.0193$, $p < 0.01$), also confirmed by the occupant of the prototype house during the monitoring period. Due to the strong correlations that were identified during the correlation analysis, the influences of the indoor operative temperature and outdoor air temperature on thermal comfort were also investigated. These correlations showed similar trends, in that a stronger correlation between the measured date/time and indoor operative temperature was identified. This can probably be explained by the fact that inappropriate cladding material was chosen for the local outdoor air temperature. Subsequently, in order to adapt to the thermal environment and make occupants feel more thermally comfortable, occupants would adjust the ratio of window openings after entering the space where they felt thermally uncomfortable.

4. Conclusion

This study investigates the building performance of a prototype house in the Building Research Establishment (BRE) Innovation Park in Garston, Hertfordshire, England, in particular assessing overheating risk issues during the long-term heatwave period. This study will be undertaken in two phases: a building performance evaluation of the case study house as a representative semi-detached terraced housing prototype in the UK, which is the focus of this paper, followed by the second and third phases, to develop an evidence-based retrofit strategy to inform the housing sector's retrofit plans. In the current phase of the study, both indoor and outdoor environmental monitoring, in-situ measurements and building simulation modelling were undertaken to assess the building performance and the impact of the energy-efficient building systems on energy use and its correlation with overheating risk issues in the summer. The results found from the monitoring during a long-term heatwave in the summer of 2018 provided strong evidence for overheating and thereby thermal discomfort in many occupied spaces, particularly on the first floor followed by several spaces on the ground floor. Meanwhile, all the occupied spaces appeared to be well above the acceptable thermal comfort benchmark throughout the data collection period. The first-hand experiences of one researcher confirmed it was often too hot in the summer to comfortably sleep in the large bedroom on the first floor due to another external heat gains factor from the BIPV solar panel systems. The data loggers corroborate occupant's views by recording temperatures above thermal comfort levels or at the higher end of the comfort range throughout the data collection period from June to July 2018.

The subsequent step was to analyse the current thermal performance of the prototype house and the potential retrofit solutions that could help improve occupants' thermal comfort, particularly during a heatwave. This was undertaken by IES modelling of the case study using real occupancy patterns, internal heat gains and detailed construction materials to validate the results obtained from the survey and indoor monitoring concerning overheating and thermal comfort. The building chosen for this case study was emblematic of a type that has raised concerned about overheating within the building and construction community. That is, thermally lightweight, terraced houses located in southeast England [53,54]. During the building's three years of operation, there was no prior indication of its likely summertime performance. The monitoring period, the summer of 2018, included a heatwave, so it was possible to see how the building would respond under conditions that will become typical as the UK climate warms. The findings from the study indicate that there is significant risk of overheating, particularly during long-term heatwaves, but also at times when there is no assessed heatwave risk. The monitoring of indoor environmental conditions revealed that, generally, indoor temperatures were high. In this case study building, the rooms on both the ground and first floors significantly exceeded the CIBSE 26°C/1% night time overheating criterion, suggesting that occupants of this building may suffer from disrupted sleep [49]. Five rooms, including the downstairs hall and the staircases' circulation areas, were chronically and severely overheated, which could render them effectively uncomfortable and therefore possibly damaging to occupants' health.

In addition to the intrinsic thermal fragility of the construction form used, other factors lent to the severe overheating risk. There was no external shading or any other form of purposefully designed overheating reduction features. The results from the rooms on the first-floor large bedroom do show that the temperatures in rooms on the southeast facing, non-shaded side are substantially higher than in the other rooms. The only form of adaptive action that the occupant might have taken was to increase the natural ventilation provided by operable windows with horizontal pine wood shading systems. This was inherently limited by the single-aspect design of the rooms and the restrictive window opening capability of 150mm which, given the external insulation of 100 to 200mm, meant the free area for ventilation was very limited indeed. In essence, there is nothing the occupant can do to escape the heat except leave their room and possibly the building.

Internal heat generation was also a factor. As well as the density of heat gain from the occupant and their electrical equipment, heat from energy storage batteries and the MVHR system leaked into the staircases' circulation area and rose up the building. In-situ measurements taken during the hottest day, 9 July, indicated that the staircases' circulation area varied from 25.7°C on the ground floor up to 29.8°C on the first floor. These circulation areas had no direct connection to the outdoors and so heat could not be ventilated away. It is worth noting that the mechanical extracts installed in this case study building, which might have exhausted some of the heat, were also ineffective. They were also very noisy and so tended not to be used; the researcher reported that the occupant preferred the ventilation system to be off. Other studies have also reported that cheap, noisy and poorly installed MVHR systems contribute to overheating risk [55].

Whilst there is no doubt that the prototype house had severe overheating problems, it was difficult to fully understand all the causes, and this is a weakness of the study. For example, although passive infrared (PIR) occupancy sensors were installed, the wireless network did not work, making it impossible to understand what contribution the operable windows made to naturally ventilate and cool down the indoor spaces, if any. Because of privacy and safety concerns, it was impossible to know reliability whether windows were opened or closed during the occupancy hours. Thus, it was not possible to calculate overheating just for the occupied periods, nor was it possible to know if adaptive actions to combat heat could have been taken.

Another limitation to the study was that it did not incorporate a questionnaire survey, so the measured temperatures could not be compared with the thermal perception of the occupant. Whilst the building itself included a variety of passive strategies that helped to mitigate the overheating risk, more could be undertaken, such as fixed or operable louvers and shutters. However, the designers acknowledged the fact that passive strategies are often missed during the early design and planning stages, in part due to their aesthetics not being common in the UK, as well as a lack of awareness of the current and future overheating risk in UK buildings throughout both the construction industry and residential sector [56,57]. The conflicts between priorities, such as health and safety, financial and quality assurance, combined with the climate change within the residential sector can also often make it difficult to 'design-in' passive measures, and further exacerbate the overheating risk. This is a significant finding in terms of enabling effective adaptation strategies to combat climate change, not just in residential buildings but also in terms of future developments. The findings of this work will provide further information for those in the construction industry, for landlords, social housing providers and tenant groups, and for those concerned with building guidelines and the regulations who wish to take action to prevent the construction of buildings that overheat. The work will also aid those concerned with the health and wellbeing of UK citizens. The monitored building would be a pilot study research project paying particular attention to the early 21st century, which has seen the construction of many toxic assets that will be uninhabitable by the mid-century.

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Conflict of interest statement

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